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EROSIONAL CONSEQUENCES OF FOREST FIRE IN THE COLORADO FRONT RANGE

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Final Report
Eisenhower Consortium for Western
Environmental Forestry Research
Project No. RM-80-107-GR (E.C. 354)
July 1981

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INTRODUCTION

Numerous studies have shown that forest fire nearly always increases the rate of soil erosion in mountain watersheds. Much of the pertinent work has been summarized in Dyrness (1967), Tiedemann et al. (1979) and Wells et al. (1979).

Fundamentally, fire reduces surface resistance to erosional processes so that critical threshold conditions for soil mobilization and transport are more readily attained (White and Wells, 1979; Swanson, 1981). Accelerated erosion appears to result primarily from removal of the protective cover otherwise afforded by the forest floor (litter and understory vegetation), leaving the soil surface exposed to the unrestrained erosive forces of raindrop splash and overland flow. Raindrop impact on bare soil directly detaches and transports soil particles over short distances. By dispersing fines, splash also tends to seal the surface. This reduces infiltration and promotes overland flow, a more competent process for the long-distance transport of eroded materials (Carson and Kirkby, 1972; Thornes, 1980).

Immediate and delayed reduction in root strength can also be an important factor in accelerated erosion after fire, particularly in coarse-textured soils on steep slopes (Krammes, 1960;

Megahan, 1978; Swanson, 1981). In addition, fire has been shown to encourage the formation or intensification of water-repellent layers at shallow depth in the subsoil (Krammes and DeBano, 1965; DeBano and Rice, 1975). This can result in substantially reduced infiltration and increased soil loss by overland flow in forest burns (Zwolinski, 1971; Megahan and Molitor, 1975; White and Wells, 1979).

A number of regional characteristics tend to enhance erosion potential in the Front Range. The area is characterized by long, steep slopes overlain by generally shallow, coarse-textured soils developed from granites, gneisses and schists (Marcus, 1973). In this type of terrain, vegetative cover tends to be of paramount importance in the regulation of geomorphic processes; removal of cover will result in rapid response to erosional forces (Carson and Kirkby, 1972; Swanson, 1981). Furthermore, in areas of high relief, coarse-textured, noncohesive soils are generally regarded by forest managers as among the most erodibile and unstable after the removal of cover by forest disturbance (Swanston and Dyrness, 1973). Experimental studies have repeatedly demonstrated the high inherent erodibility of sandy soils (Farmer, 1973; Bryan, 1974; Luk, 1979). It has also been shown that coarse-textured soils are most prone to develop severe water-repellancy (Meeuwig, 1971a; DeBano and Rice, 1975).

Climatic conditions in the Front Range similarly favor erosion. Intense convective rainstorms are common during the snow-free season. Low annual precipitation, high radiation and high evapotranspiration make the climate semiarid to subhumid (Gary, 1975; Hansen et al., 1978). Resulting low soil moisture levels

should delay vegetative recovery after burning, particularly on south-facing slopes. Because of these general climatic conditions, fire has long been an important environmental factor in the Front Range and the character of the present forest cover reflects its recurring influence (Marr, 1967; Barrows, 1977).

This study is an attempt to delineate the broader aspects of hillslope erosion after forest fire on the east slope of the Front Range. Specifically, research efforts were designed to determine 1) the effect of burn intensity on the relative magnitude of erosion, 2) the influence of local site characteristics on soil loss, 3) the source areas of soil loss within burned areas which contribute the bulk of the sediment released to the active drainage network and 4) changes in the magnitude of erosion over time. This paper summarizes the major findings of this work.

BACKGROUND

The composition of the mixed-conifer forest on the east slope of the Front Range changes along an altitudinal gradient from lower foothills to forest-tundra ecotone near the summit of the range. In general, dominant overstory vegetation varies from ponderosa pine (Pinus ponderosa) and Douglas fir (Pseudotsuga menziesii) above approximately 6000 feet (1830 m), through mixed stands of ponderosa pine, Douglas fir, lodgepole pine (Pinus contorta) and aspen (Populus tremuloides) between roughly 8000 and 9000 feet (2440-2745 m), to Engelmann spruce (Picea engelmannii) and subalpine fir (Abies lasiocarpa) forest extending up to around 11,000 feet (3355 m) (Marr, 1967). Virtually the entire forested area shows signs of extensive historical disturbance from mining,

grazing, lumbering and fire (Marr, 1967; Gary, 1975).

Litter cover is relatively continuous in the absence of recent disturbance and overland flow is uncommon in these sites (Gary, 1975; Leaf, 1975). Active erosion in small areas of bare ground within the forest is primarily limited to rainsplash (Bovis, 1978). Where disturbance has been particularly recent or severe, however, much of the surface may be essentially bare and often consists of erosion pavement, particularly on south-facing sites with less forest cover (Gary, 1975). Texturally, surface soils are gravelly sandy loams or loamy sands; these thin, residual soils occur over about 90 percent of the area in the Front Range (Marr, 1967; Gary, 1975).

Mean annual precipitation is relatively low, from approximately 15 inches (38 cm) at lower elevations to 30 inches (76 cm) or more at higher elevations. Precipitation amounts are extremely variable from year to year. Maximum precipitation occurs in the spring (generally as snow at higher elevations) and summer (as thundershowers) (Gary, 1975; Hansen et al., 1978). Gary (1975), citing Love (1958), indicates that maximum 10-minute rainfall intensities average 3 to 3.5 inches per hour (7.6-8.9 cm/hr.) for summer thundershowers in this region. This is well within the range of values associated with the maximum kinetic energy (and therefore erosivity) of rainfall (Evans, 1980). Rainfall intensity-duration data such as these, however, are highly generalized and are based on a short and areally inadequate record; it is probable that much higher short-duration rainfall intensities are common in this area (Hansen et al., 1978). The destructive 1976 storm in the Big Thompson drainage apparently generated rainfall

intensities of nearly 22.5 centimeters per hour (8.9 in/hr.) at some localities (Balog, 1978).

Data for this study were collected during the summer-early fall period of 1980. The summer of 1980 was characterized by above normal temperatures and below normal precipitation throughout the Front Range, especially in June and July (U.S. Dept. Commerce, 1980). Estes Park (elevation 7525 ft.; 2295 m), near the center of the general study area (Figure 1), received only 2.39 inches (6.07 cm) of rainfall from June through August compared to normal precipitation of 6.27 inches (15.93 cm) for this period (U.S. Dept. Commerce, 1980). Because of these conditions, fires were common during the summer. One large fire in late June (Bear Trap) provided an opportunity to gain information on erosional response in a very fresh burn.

STUDY AREAS

Five separate burned areas along the east slope of the Front Range were investigated (Figure 1). Much of this area is within Roosevelt National Forest but portions fall within other jurisdictions. Specifications of these sites, including date of the burn, are summarized in Table 1.

Study areas appear to be generally similar to each other with respect to soils, topography and drainage. The greatest differences undoubtedly exist between the Ouzel study area, which was glaciated as recently as Wisconsin (Pinedale) time, and the other four sites, which have not been glaciated. In all areas instrumentation and sampling was limited to hillslope sections. At the unglaciated sites these are underlain by residual debris or

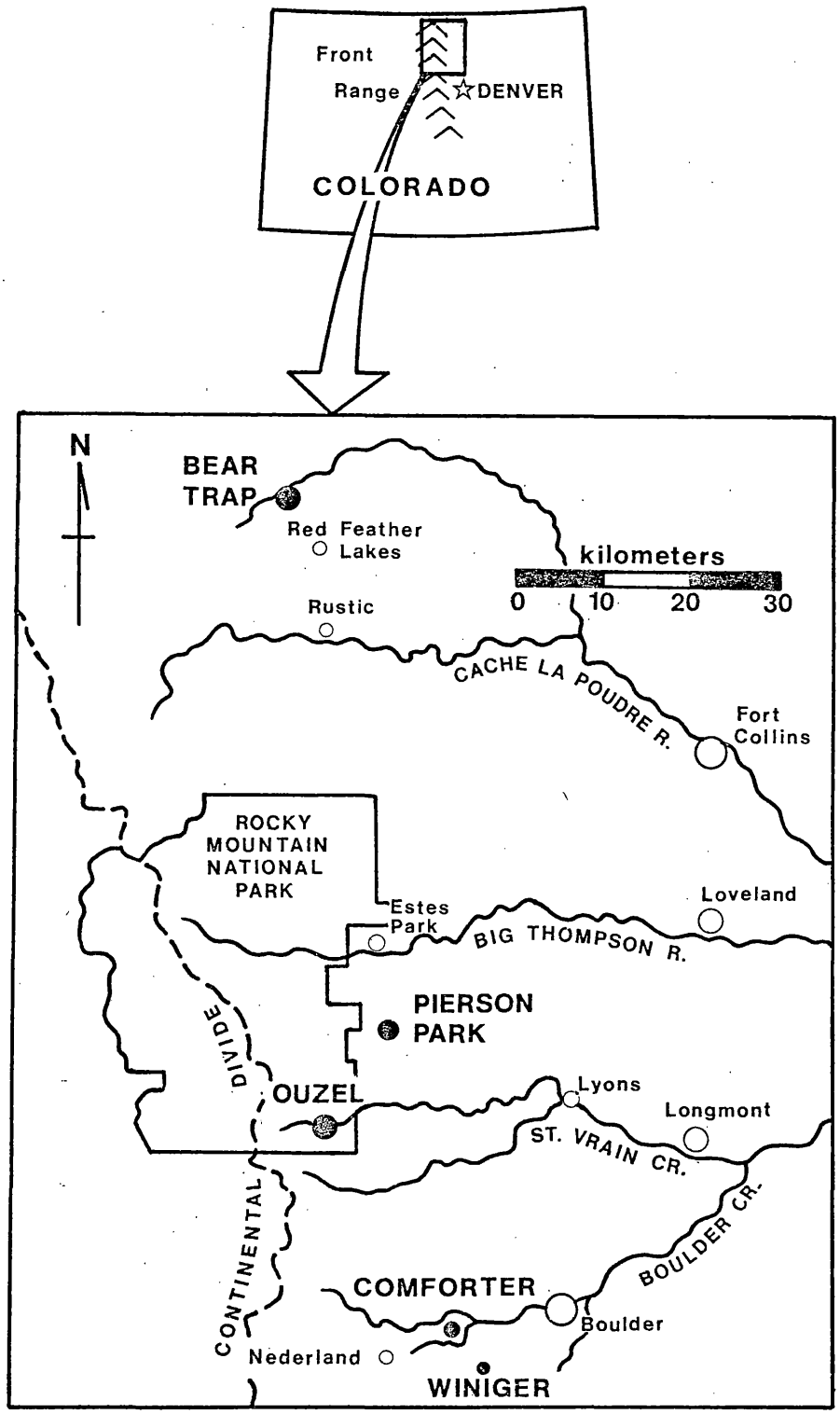

Figure 1. Location map showing the general study area on the east slope of the Colorado Front Range. Specific study sites are shown in bold-face type.

Table 1. Specifications of study sites.

Fire Name	Date of Burn	Location	Ownership	Acreage (hectare)	Approx. Elev. a.s.l. ft. (m)	Cover Types
Comforter Mountain	June 1976	T.1 S., R.72 W. Boulder County	Private and N.F.	256 (104)	7800-8300 (2379-2532)	Ponderosa pine
Ouzel (Wild Basin)	Sept. 1978	SE corner of Rocky Mtn. N.P.	National Park Serv.	1050 (425)	9000-11,200 (2745-3416)	Lodgepole p./ spruce-fir
Winiger Point	Sept. 1978	T.1 S., R.71 W. Boulder County	N.F. and Denver Water	19 (8)	7300 (2227)	Ponderosa p. (cutover)
Pierson Park	Oct. 1979	T.4 N., R.72 W. Larimer County	N.F.	312 (126)	9300-9800 (2837-2989)	Lodgepole pine
Bear Trap	June 1980	T.11 N., R.74 W. T.11 N., R.73 W. T.10 N., R.74 w. Larimer County	N.F. and	2734 (1107)	8500-9900 (2593-3020)	Lodgepole p./ ponderosa p.

*N.F.= National Forest land.

colluvium; at Ouzel, soils are at least in part developed on glacial till. In addition to these factors, each study area must differ somewhat with respect to vegetation, local climate and land-use history. Though erosional process-response characteristics appear to be similar at all sites, comparisons between study areas must be viewed with these limitations in mind.

Total summer rainfall for the period of observation/instrumentation at each study area is summarized in Table 2. Precipitation was recorded on-site with bucket-type rainguages which were periodically measured and emptied. Where this record is unavailable because of disturbance, precipitation is reported as the amount recorded at the nearest Weather Service station (U.S. Dept. Commerce, 1980).

Table 2. Total precipitation at study areas during the field season, summer, 1980.

Site	Period of Record	Total Rainfall inches	(cm)
Bear	July 22 - Sept. 23	3.29	(8.36)*
Pierson	June 17 - Sept. 16	4.26	(10.80)
Ouzel	July 9 - Sept. 15	3.86	(9.80)
Winiger	June 29 - Sept. 14	4.15	(10.54)+
Comforter	June 24 - Oct. 3	5.00	(12.70)

*Red Feather Lakes station.
+Gross Reservoir station.

Unfortunately, a large number of instrumented locations in the Pierson, Comforter and Winiger study areas were disturbed during the course of the summer as a result of fuelwood-cutting

activity by the public. At the Pierson and Comforter sites, which were the most intensively instrumented of any of the study areas, a large amount of potential information was lost as a result of this activity. Nearly all instrumentation was destroyed at Winiger. Only data from locations within these study areas which did not appear to be disturbed are included for analysis. In some cases it was possible to use data from the portion of the instrument record prior to disturbance.

METHODS

Determination of on-site erosion involved both the observation of evidence of erosion at each study area as well as instrumentation to measure the local magnitude and variability in erosion over the field season. Reconnaisance of the study sites at the beginning of the field season indicated that post-fire erosion was most pronounced in severely-burned areas. Because of this, instrumentation was concentrated in these areas. A lesser number of instrumented networks were installed in moderately-burned, lightly-burned and adjacent unburned control areas, respectively, though these areas were continually observed for any evidence of fresh erosion.

Severity of burning was classified on the basis of a visual appraisal of the condition of the overstory, forest floor and soil surface and is similar to the classification employed by White and Wells (1979) (Table 3):

Table 3. Burn intensity classification.

Descriptive Classification	Classification Criteria
Severe Burn	All ground and tree foliage destroyed, leaving only charred trunks and larger branches in the overstory.
	Only charcoal and ash, and deeply charred larger debris, remain on the soil surface.
Moderate Burn	Trees killed but retain smaller branches and dead needles in the crown; depending on crown density, needlefall is generally abundant shortly after the fire.
	Ground foliage is destroyed but patches of charred litter survive.
Light Burn	Trees generally survive with most or all of crown intact.
	Scorched litter cover remains and some shrub foliage may survive.
Unburned	No evidence of recent burning.

Field instrumentation consisted primarily of one-meter-long "stations", aligned perpendicular to the slope, positioned along longitudinal- and cross-profile transects. Because of access, time and equipment constraints, no attempt was made to apply a random or systematic sampling design in selection of sites for instrumentation. As it was considered most important to monitor erosional activity over the range of conditions encountered on these heterogeneous hillslopes, station networks were situated to incorporate a variety of local site characteristics (in terms of slope, cover, etc.) within each study area. A total of 203 stations were installed, though a large number of these were subsequently disturbed. Despite this unavoidable reduction in

sample size, as well as sampling design limitations, it is felt that adequate representation remains to permit valid comparisons between study areas.

Stations consisted of two 24 inch (61 cm) lengths of 0.5 inch (1.3 cm) diameter reinforced steel bar driven into the surface approximately one meter apart and leveled to provide stable benchmarks for repeated survey of ground surface elevation. This was accomplished using a "profile frame" consisting of aluminum angle fashioned into a rigid frame which provided support for 21 slender probes positioned 5 centimeters apart. With the frame placed on the benchmarks, the probes could be lowered to the surface for elevation determination against a constant datum. This device allowed precise determination (within $\pm$ 3 mm on a firm surface) of the ground surface profile along one meter of contour with minimal disturbance of the site. Initial readings were used for a measure of surface roughness. A meter-long paintline was inserted between monuments to monitor evidence of particle displacement by splash or wash.

At selected stations, 50 centimeter-long Gerlach troughs (sediment traps) were installed approximately one meter below the paintline to capture any soil mobilized within the area immediately upslope. These were left uncovered and were not bounded by a plot frame. Traps were constructed of half-round plastic gutter (0.165 m^3 total capacity) and were installed with the upslope lip of the trap flush with the mineral soil surface. A total of 80 traps were installed; 20 of these, mostly in severly-burned sites, were disturbed.

Groundcover density (vegetation and litter) immediately

upslope of stations and sediment traps was estimated with the aid of a quadrat (1 m^2). Bulk density of the upper 5 centimeters of the soil was measured gravimetrically in the field. Soil strength was also measured in the field with a portable penetrometer and vane shear device. An attempt was also made to measure relative infiltration rate with a double-ring flooding-type infiltrometer. Results from these tests were unsatisfactory because of unavoidable site disturbance and leakage in these coarse-textured soils.

Samples of the upper 5 centimeters of the soil upslope of sediment traps were taken at the end of the field season. Soil particle-size distribution was determined by sieve and pipet analysis; organic matter content was determined by ignition.

Though all of these soils are only weakly-aggregated, a rough measure of the proportion of primary mineral particles less than two millimeters diameter combined into larger structures (greater than 2 mm) was devised. Prior to mechanical analysis, the weight percentage of air-dry soil in the greater than two millimeter bulk fraction was determined by gently shaking the material over nested sieves (2, 4, 8 and 16 mm mesh). After comminution and sieving (leaving only stones in the greater than 2 mm fraction) this proportion was again determined. The percent difference of the bulk soil sample in the greater than two millimeter fraction before and after comminution is a measure of the proportion of primary particles (sand-silt-clay) combined into larger structures (at this scale, the weight of fine unincorporated organic matter passing through the two millimeter mesh is negligible). Much of the apparent aggregation observed in these secondary

structures (especially in those greater than 8 mm diameter) appears to result from the binding together of mineral grains and smaller aggregates by fine, dense root networks. Where they are abundant, these impart considerable mechanical strength to the structures.

Soils (less than 2 mm fraction) were also lab tested for water-repellancy using the water drop technique, a simple method which is often employed in the field (Krammes and DeBano, 1965; Megahan and Molitor, 1975).

Contents of the sediment traps were collected at the end of the field season and analyzed with respect to total oven-dry weight of both the mineral and organic fractions as well as the particle-size distribution of the sediment.

RESULTS

Measured Soil Loss

Average values of soil loss in each of the study areas was determined from the total amount of material collected in sediment traps by the end of the study period (Figure 2, Table 4). (The Winiger Point site was excluded because of inadequate sample size as a result of disturbance.) Only traps positioned in essentially "open" (straight-contour) hillslope situations are included in the results; traps installed within obvious surface drainage features and gullies are excluded.

The record does not necessarily reflect the total amount of material mobilized above all traps because of the irregular and discontinuous pattern of slopewash in these areas. At the Bear

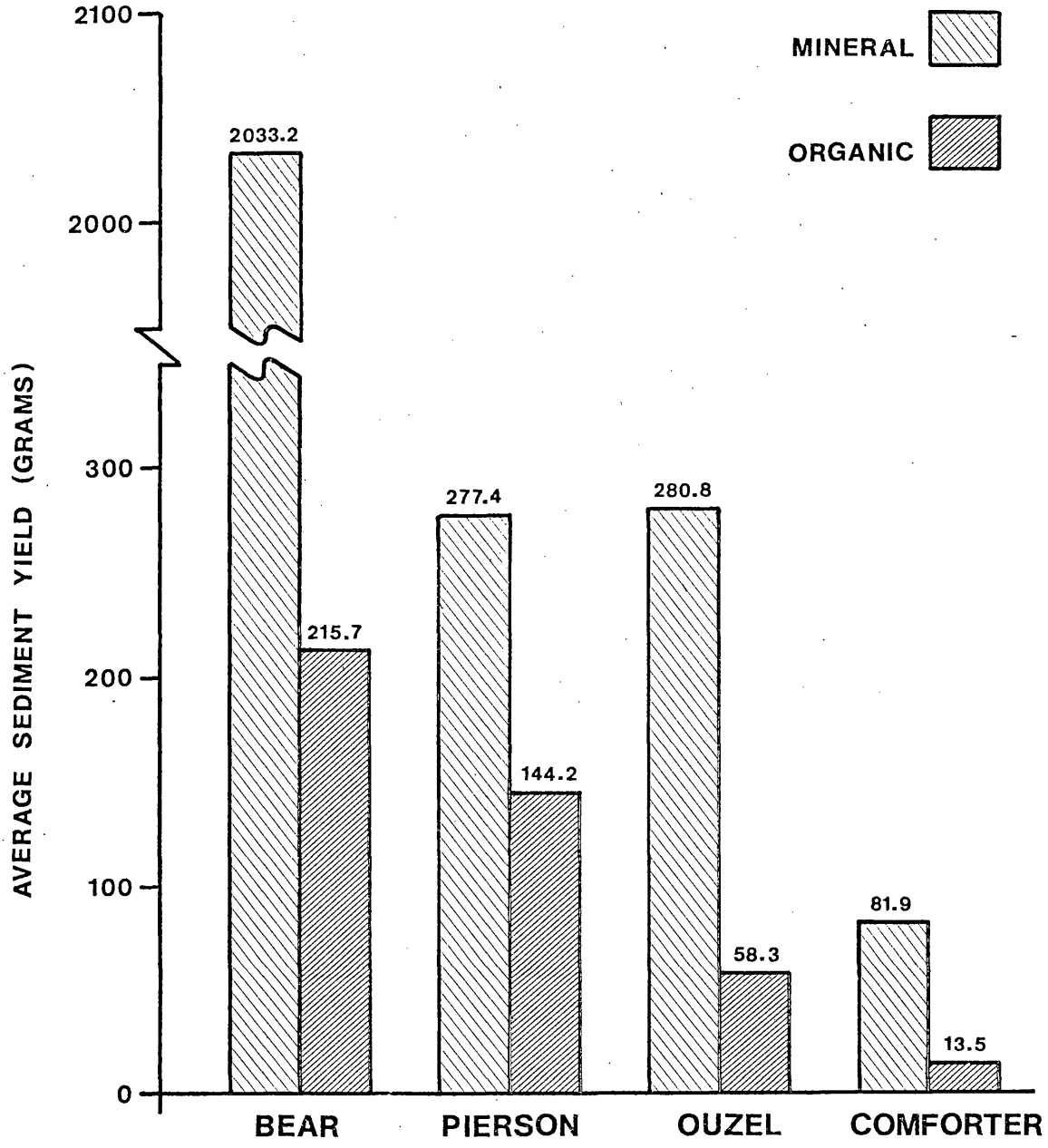

Figure 2. Mean oven-dry weight of total sediment collected in sediment traps over the duration of the study period at each burn site.

Trap site, in particular, observations indicated that the catch in the traps under-represented surficial erosion: many of the traps were filled to overflowing when their contents were collected.

Most of the traps which accumulated measurable quantities of sediment are within severely-burned situations (Table 4). Except at Bear, moderately- and lightly-burned areas generally experienced little if any soil loss, as evidenced by both the sediment trap record and field observations.

Table 4. Duration of the sediment trap record at study areas, summer, 1980.

Site	Sample Size (# in severe burn)	Period of Record Begin	End	Total Days*
Bear	8 (6)	7/22	9/23	62
Pierson	9 (7)	6/17	9/16	90
Ouzel (West)	5 (5)	7/9	9/15	67
(East)	6 (5)	7/26	9/15	50
Comforter	9 (8)	6/24	10/3	100

*Not including dates of installation and collection.

Results strongly suggest a pattern of declining sediment production over time (Figure 2). The fresh burn at Bear experienced by far the greatest amount of soil loss of any of the study areas. On the other hand, Comforter, the oldest burn, sustained only relatively modest erosion despite the longer record (100 days vs. 62 days) and greater total rainfall (12.70 cm vs. 8.36 cm) here.

An analysis of variance (ANOVA) and Duncan's multiple range

test showed that sediment yield at Bear was significantly different (at the 0.05 level tested) from that at the three older sites. Total mineral material collected at Bear ranged from a minimum of 270.3 grams to a maximum of 4001.8 grams. All study areas showed a similar wide range in the quantity of material trapped, an indication of the irregular pattern of erosion over the hillslopes which was observed in the field. Measurable mineral sediment yield at Comforter ranged from a low of 11.9 grams to a high of 186.0 grams. Because of this wide range, Duncan's test grouped average yield at Comforter with the averages for the burns of intermediate age (Pierson and Ouzel).

Though Pierson and Ouzel show no significant differences in the average weight of accumulated mineral sediment, real differences in yield do exist between these study areas. The average values of organic and mineral sediment collected in traps at Ouzel reflect the combined results from two quite dissimilar sites, 2.1 kilometers (1.3 miles) apart, at that study area. These sites are differentiated in Table 4. Ouzel West is on a south-facing slope with an average gradient above the traps of 15 degrees. Ouzel East comprises a north-facing slope with an average gradient above the traps of 29 degrees. Average mineral sediment yield at Ouzel West was 506.5 grams while that at Ouzel East was 92.6 grams. Sample size in each of these locations was too small for separate consideration in Figure 2.

Differences in sediment yield between the two sites within the Ouzel study area cannot be related to the shorter record at Ouzel East (Table 4) because little rainfall occurred before the traps were installed here and virtually no sediment had collected

in the traps at Ouzel West during this period. The disparity in rates of soil loss appears to be a reflection of differences in the "relative age" of the two locations. Ouzel East appears to have experienced greater erosion sooner after burning than the Ouzel West site, probably because of greater slope here. As a result, surface soils at Ouzel East are now essentially a lag gravel which armours the surface against further significant soil loss.

ANOVA also showed significant differences in organic sediment yield between burned sites. Both Bear and Pierson were significantly different (at the 0.05 level) from each other and the other study areas but Ouzel and Comforter did not differ significantly. Again, large differences exist between the two locations at Ouzel: average organic loss at Ouzel East (the steeper site) was only 22.1 grams while that at Ouzel West was 101.7 grams. Duncan's multiple range test indicated that the greatest difference in yield of organic material exists between the youngest burns (Bear and Pierson) and the oldest burns (Ouzel and Comforter). The regular decline in organic yield with time since burning (Figure 2) appears to reflect both the progressive removal of loose charcoal and ash by surface wash and wind, and accelerated decomposition and reduced renewal of organic material in exposed, severely-burned sites.

Surface Elevation Change

Change in the elevation of the ground surface at a large number of points within each study area was determined by repeated measurement with the profile frame. The absolute values of the

change at 5 centimeter intervals over one meter were summed to give a measure of total change at each station. In addition, net change (gain or loss) was determined. The values for all stations within each study area were then used to give an average value of both absolute and net surface change (Table 5). Values have been weighted for differences in sample size between areas and the variable length of record (due to site disturbance) within several of the study areas.

Only data from severely-burned sites, where virtually all of the observed erosion occurred, are reported. Measurements in moderately-burned, lightly-burned and unburned control sites are of little value because of the pliant nature of the litter cover in these areas: repeated measurement often revealed large differences in ground surface elevation where clearly no real change in the soil surface had occurred.

Table 5. Average surface elevation change in severely-burned locations within study areas, summer, 1980.

Site	Length of Record (days)*	Sample Size	Absolute Change (mm)	Net Change (mm)
Bear	62	10	53.6	-49.8
Pierson	95	31	47.1	-36.1
Ouzel (West)	67	18	46.8	-16.2
(East)	66	8	49.3	-4.5
Comforter	104	17	15.0	-3.7

*Exclusive of installation and final measurement dates.

Results of these measurements clearly support the soil loss data: maximum geomorphic activity, as indicated by the absolute surface change figures, is occurring in the most recent burn (Bear) while the lowest level of activity is indicated for the oldest site (Comforter). In addition, the youngest and oldest areas show the greatest and least net loss, respectively.

The absolute change values are probably the most realistic measures of the level of geomorphic activity at each study area. Field observations showed that, in actively eroding areas, degradation and deposition alternate along and across the hillslope profile. Though net change values consistently show a loss, the lower values (Ouzel East and Comforter) are probably more an effect of settling and compaction of the soil surface than actual erosional loss. This is also suggested by observations at individual stations at these locations, many of which exhibited measured net loss though no actual removal of material was evident.

In contrast, the higher net change values are clearly related to actual soil loss at the majority of stations within these study areas: 9 out of 10 stations at Bear and 25 out of 31 stations at Pierson registered net loss. Most stations at these locations (and Ouzel West), exhibiting both net loss and gain, were crossed by surface wash features and minor rills during the course of the field season. Though considerable erosion occurred at Ouzel West, the exceptionally rough surface here (moraine) resulted in deposition (net gain) at many of the stations; 10 out of 18 stations showed net loss. At Ouzel East and Comforter, where erosion was relatively slight, 2 out of 8 and 11 out of 17

stations, respectively, experienced measured net loss in surface elevation.

The data for Ouzel East appear equivocal: though net loss is low, absolute surface change is high. While this site experienced little net erosion during the study period, material is gradually being moved by splash and dry creep and sliding (ravel). Almost no vegetation has returned to this site and without cover and binding root networks this steep slope is extremely unstable. Because of the stoniness of the surface soil, minor particle movements result in a relatively large change in surface elevation.

Textural Analysis

Average textural differences between all soils sampled within burns (sample size = 56) and all sediment collected in traps in burned areas (sample size = 42) are shown in Figure 3. Particle-size distributions were determined from the weight-percent of the oven-dry bulk soil sample in the following diameter classes: pebble (greater than 4 mm), granule (4-2 mm), sand (2-0.05 mm), silt (0.05-0.002 mm) and clay (less than 0.002 mm). Data plotted in Figure 3 include the limited sample available from the Winiger study area. Most of the cases within each sample are from severely-burned sites; plotting data from only severely-burned sites gives almost identical results.

Average values for each of the textural separates, in soil and sediment, respectively, are as follows: pebble: 21.2 and 9.6 percent; granule: 11.5 and 11.7 percent; sand: 46.4 and 52.4 percent; silt: 16.3 and 18.7 percent and clay: 4.6 and 7.6 percent.

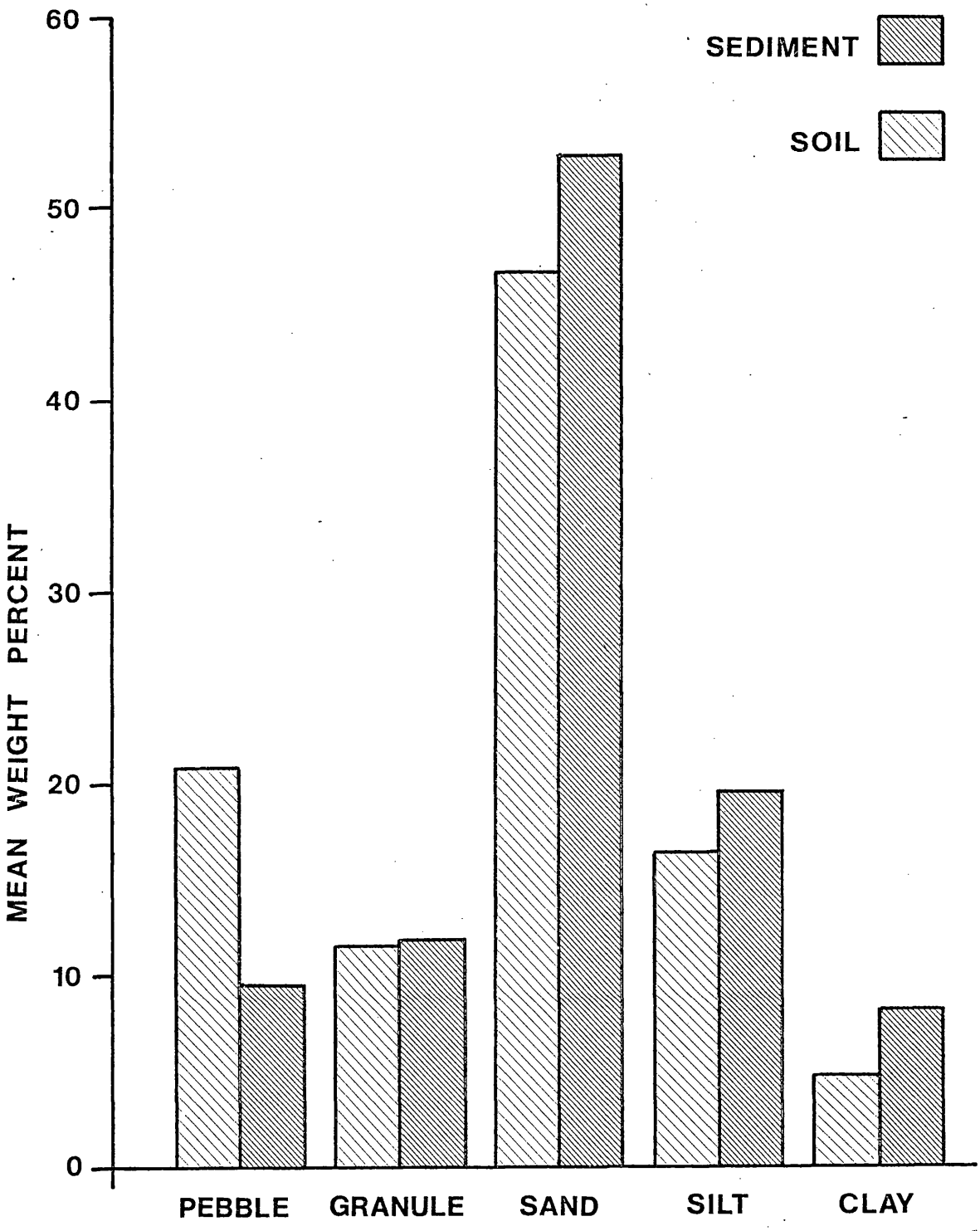

Figure 3. Average grain-size distribution of all soils within burns and all sediment collected in traps within burns.

When compared by means of a Student's t-test, differences in pebble, sand and clay content proved to be significant (at the 0.05 level tested) while differences in granule and silt content were not significant at this level.

These results, grouping the full range of slope and soil textural conditions sampled, show an overall trend of decreased grain-size for sediment compared to that of the original soil. Thus, fines are progressively removed from eroding areas while coarse material is retained.

Table 6. Average grain-size distributions for severely-burned locations within study areas.

Site	Material	Sample Size	Average Wt. Percent Gravel	Sand	Silt-Clay
Bear	Soil	6	37.0	40.2	22.8
	Sediment	6	25.6	53.2	21.2
Pierson	Soil	6	38.1	43.7	18.2
	Sediment	6	15.5	45.6	38.9
Ouzel (West)	Soil	5	32.1	40.4	27.5
	Sediment	5	3.0	52.7	44.3
Ouzel (East)	Soil	5	47.6	40.9	11.5
	Sediment	5	40.1	50.6	9.3
Comforter	Soil	9	25.5	63.4	11.1
	Sediment	8	24.4	64.6	11.0

Comparisons of the textural properties of soil and sediment at each of the study areas give more meaningful results since local site factors are controlled for (Table 6, Figure 4). In addition, only data from severely-burned portions of each study

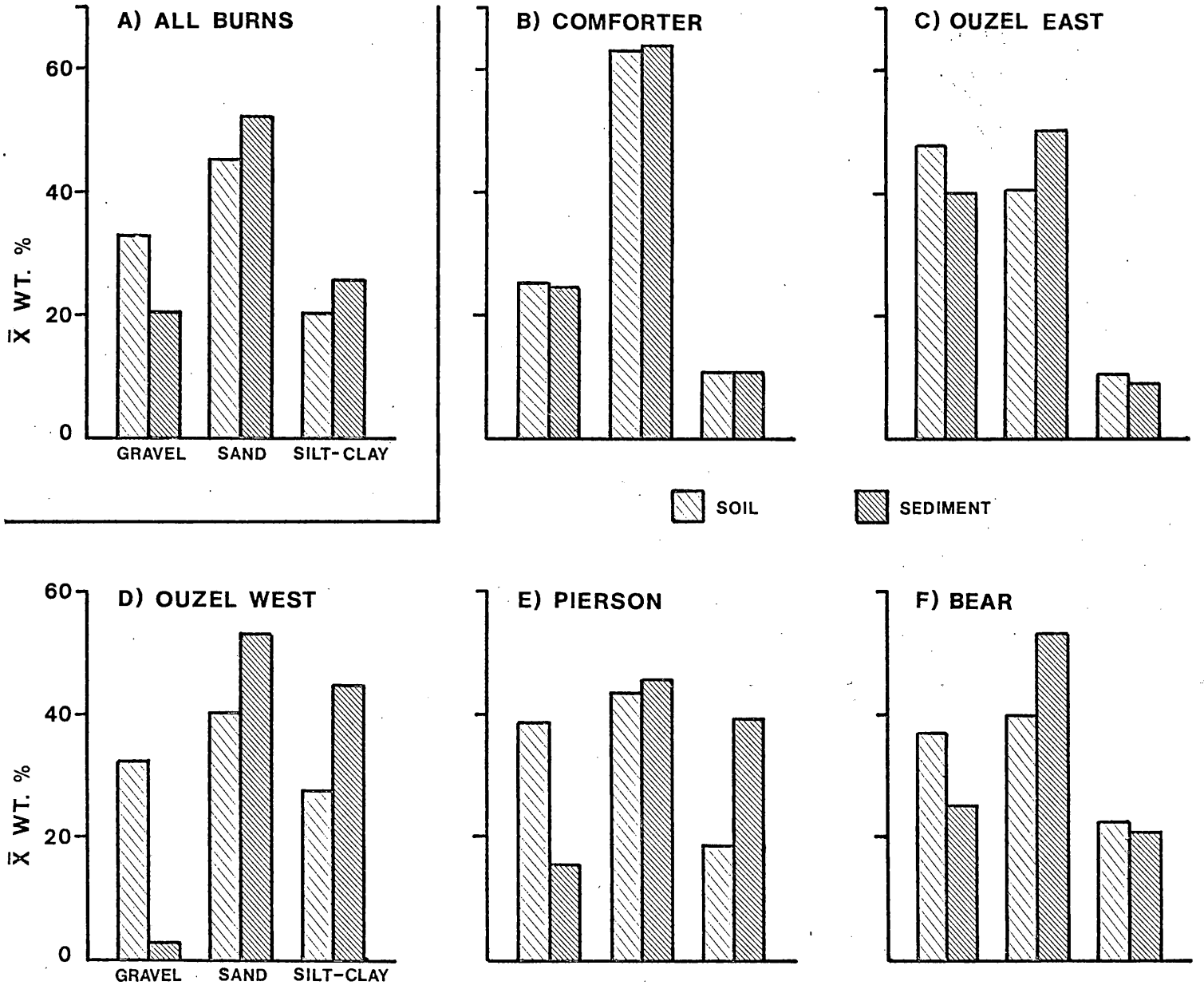

Figure 4. Average grain-size distributions of soil and sediment from severely-burned locations within study areas (B through F). A (box) shows the data in Figure 3 in this textural classification.

area (locations experiencing most erosion) are shown in these results. To clarify the important trends in grain-size frequency distributions, data are given in the following diameter classes: gravel (greater than 2 mm), sand (2-0.05 mm) and silt-clay (less than 0.05 mm).

Paired-sample t-tests were applied to paired station (soil/sediment) data; for these tests all stations within burns with traps which collected sediment were used to retain sufficient degrees of freedom for test significance. However, as previously indicated, most of these stations are in severe burn locations. Results showed that gravel content between original soil and sediment was significantly different (at the 0.05 level) at Bear, Pierson and Ouzel West; differences at Ouzel East and Comforter were not significant (Figure 4, Table 6). Thus, in areas undergoing appreciable erosion (as determined from both sediment yield data and field observations), losses occur primarily in the finer fractions. In contrast, in areas presently experiencing minimal erosional loss (Ouzel East and Comforter), particle-size proportions between original soil and sediment are more nearly similar. These relationships are well shown in Figure 4.

To further clarify the relationship between particle-size distribution of the surface soil and rate of soil loss, mean grain-size (phi scale) of soil and sediment was obtained using the method of moments technique with the weight-percent sand-silt-clay (Krumbein and Pettijohn, 1938). Mean values from each study area were averaged to give the results shown in Table 7:

Table 7. Average mean grain-size (MØ) of soil and sediment (less than 2 mm fraction) from study areas.

Site	Sample Size*		Mean Grain-size (Ø)	
	Soil	Sediment	Soil	Sediment
Bear	10 (6)	8 (6)	3.82	3.75
Pierson	9 (6)	9 (7)	3.33	3.96
Ouzel (All)	11 (10)	11 (10)	3.41	3.41
Ouzel West	5 (5)	5 (5)	3.90	4.27
Ouzel East	5 (5)	5 (5)	2.83	2.52
Comforter	9 (9)	8 (8)	2.50	2.51

*Number in sample from severely-burned sites in parentheses.

These data show that both soil and sediment in areas presently experiencing the most erosion (Bear, Pierson and Ouzel West) are finer-textured (larger MØ) than they are at Comforter and Ouzel East, where erosional losses are low. As erosion favors smaller grain-sizes, the lower erosion rates at these last two study areas can probably be attributed, in large measure, to the limited availability of easily entrained and transported material here.

Furthermore, results of the textural analyses represent the condition of the surface 5 centimeters of the soil. Observations in the field at both Ouzel East and Comforter show that the surface one to two centimeters of soil is actually appreciably coarser than the textural measures would suggest. The soil surface at these locations is veneered with a lag gravel which reduces erosion by armouring the surface (Figure 5). Surface armouring at Comforter appears to be primarily an effect of time since burning while that at Ouzel East may reflect exceptionally rapid

Figure 5. The steep slope at Ouzel East nearly two years after burning. Note the coarse texture of the surface soil which effectively armours the hillslope, greatly reducing erosion. Scale is 20 cm.

erosion on the steep slope here after de-vegetation. Ouzel West, of the same age but with a much shallower slope, continues to erode at a greatly accelerated rate.

Progressive surface armouring can be illustrated by comparing textures of unburned soils, soils within burns and sediment at the Bear and Comforter study areas (Table 8):

Table 8. Average grain-size distribution data for unburned soil, burned soil and sediment at the Bear and Comforter study areas.

Site	Material	Sample Size	Average Wt. Percent (less than 2 mm fraction) Sand	Silt	Clay	MØ
Bear	Unburned soil	8	65.1	28.1	6.8	3.59
	Burned soil	10	60.7	32.0	7.3	3.82
	Sediment	8	63.4	22.5	9.1	3.75
Comforter	Unburned soil	8	73.1	20.2	6.7	3.19
	Burned soil	9	85.1	11.4	3.5	2.50
	Sediment	8	85.6	10.0	4.4	2.51

Differences in the averages of mean grain-size (MØ) of the different materials at each site were tested using ANOVA and Duncan's multiple range test techniques. Results showed that no significant difference exists between unburned soil, burned soil and sediment at Bear. On the other hand, unburned soil is significantly different (at the 0.05 level tested) from both the burned soil and sediment at Comforter. Student's t-tests on the mean grain-size values showed that while unburned soils at Bear and Comforter are not significantly different, both burned soil and sediment do differ significantly (at the 0.05 level) between the

two sites.

Kirkby (1980) has recently discussed surface armouring in terms of the complex response to erosional processes exhibited by hillslopes as surface conditions are gradually altered. After disturbance, accelerated erosion selectively removes finer grain-sizes from the soil surface. As this process continues, and the surface becomes progressively coarser, erosion must ultimately diminish because the size of remaining particles exceeds the capacity of erosional processes to detach them.

Bear clearly represents the transport-limited situation of a newly burned area: de-vegetation has drastically lowered the threshold conditions necessary for soil loss to occur and an abundance of erodible material is available for transport if erosive force is applied.

Progressive erosion eventually produces the detachment-limited condition exemplified by Comforter. In this case, though threshold conditions remain below those of the unburned forest, the development of a coarse lag deposit at the soil surface effectively limits erosional losses.

Water-repellancy

The occurrence of water-repellent soils was not systematically evaluated in the field. However, spot-checks conducted in all study areas seemed to indicate that it was more common in the newer burns than in the older sites. In all areas its occurrence appeared highly variable, both with depth and areally over the surface.

Despite the apparently "spotty" nature of water-repellancy

observed in the field, significant results were obtained when soils were lab tested using a simple water drop technique. A further potential source of error associated with the method used here was that throughly mixed soil samples were tested. Since disturbance could mask the influence of any thin water-repellent layers present in the in situ soil (Krammes and DeBano, 1965), the results of these tests were all the more striking.

The tests involved applying several drops of distilled water to approximately 50 gram samples of air-dry soil (less than 2 mm fraction). Soil hydrophobia was considered absent if the water drops penetrated the soil immediately after application. Soils were deemed "weakly water-repellent" if the water drops beaded-up on the surface but penetrated in less than 10 minutes. In most cases, drops penetrated these soils within a few minutes after application. Soils were to be considered "strongly water-repellent" if penetration time was in excess of 10 minutes (in all cases tested, more than one hour was required before the water drops disappeared into the surface in strongly water-repellent soils).

Out of 20 soils exhibiting strong water-repellency, all but four required in excess of 8 hours for the water to infiltrate into the soil. These soils also strongly resisted vigorous mechanical mixing of water into the soil.

Though the possibility exists that resistance to wetting could be at least partially related to the low initial moisture content of the air-dry soil (generally on the order of 2 to 3 percent), studies have shown that where strong hydrophobic tendencies are indicated it is usually due to a more permanent

property of the soil (Krammes and DeBano, 1965). Furthermore, many of the soils tested here which exhibited no water-repellency were as dry as or drier than soils showing this effect.

Soil samples from all burn-intensity conditions within each study area were grouped together in these tests. Though most of the soils were from severely-burned sites there did not seem to be any regular variation in water-repellency between burn conditions within any one study area. Results of the tests are shown in Table 9:

Table 9. Occurrence of water-repellancy in soils from study areas (as number of samples showing specified degree of non-wettability).

Site	Water-repellancy: Absent	Weak	Strong	Total Sample
A. Soils within burns:				
Bear	0	3	9	12
Pierson	0	4	9	13
Ouzel	3	10	1	14
Winiger	2	3	0	5
Comforter	10	2	0	12
B. Unburned soils:				
Bear	5	3	0	8
Comforter	4	4	0	8

Test results show a strong tendency towards reduced water-repellency with elapsed time since burning. While 72 percent of the soils tested from the newer burns (Bear and Pierson) show

strong hydrophobic tendencies only one soil of the 31 tested from burns more than one year old (Ouzel, Winiger and Comforter) exhibited this degree of water-repellancy.

The significance of these results were tested by chi-square. Differences in non-wettability between the newer burns and the older sites were highly significant (X^2 = 40.10 with 2 degrees of freedom; $p < 0.001$). Differences in water-repellancy between the newer burns and the unburned soils were also highly significant (X^2 = 25.56 with 2 degrees of freedom; $p < 0.001$). In contrast, water-repellancy in the older burns was not significantly different (X^2 = 0.05 with 1 degree of freedom) from that exhibited by the unburned soils.

While examination of the data shows no specific relationship between measured soil loss (amounts collected in sediment traps) and water-repellency, a link between erosion and soil non-wettability is clearly suggested. The Bear and Pierson study areas exhibited the most pronounced occurrence of water-repellency as determined by the method used here and likewise experienced major soil losses during the field season. Though Ouzel West also had large erosional losses during this period only weak hydrophobic tendencies were evident in the soils tested from this location. Nevertheless, these results represent an extremely limited sample of a few isolated points on the hillslope. Severe water-repellency was found at several locations in the field at Ouzel West (figure 6).

Limited field testing indicated a general absence of water-repellency in the soil at Comforter. Laboratory results confirmed this finding: of the 9 soils sampled from the severely-burned

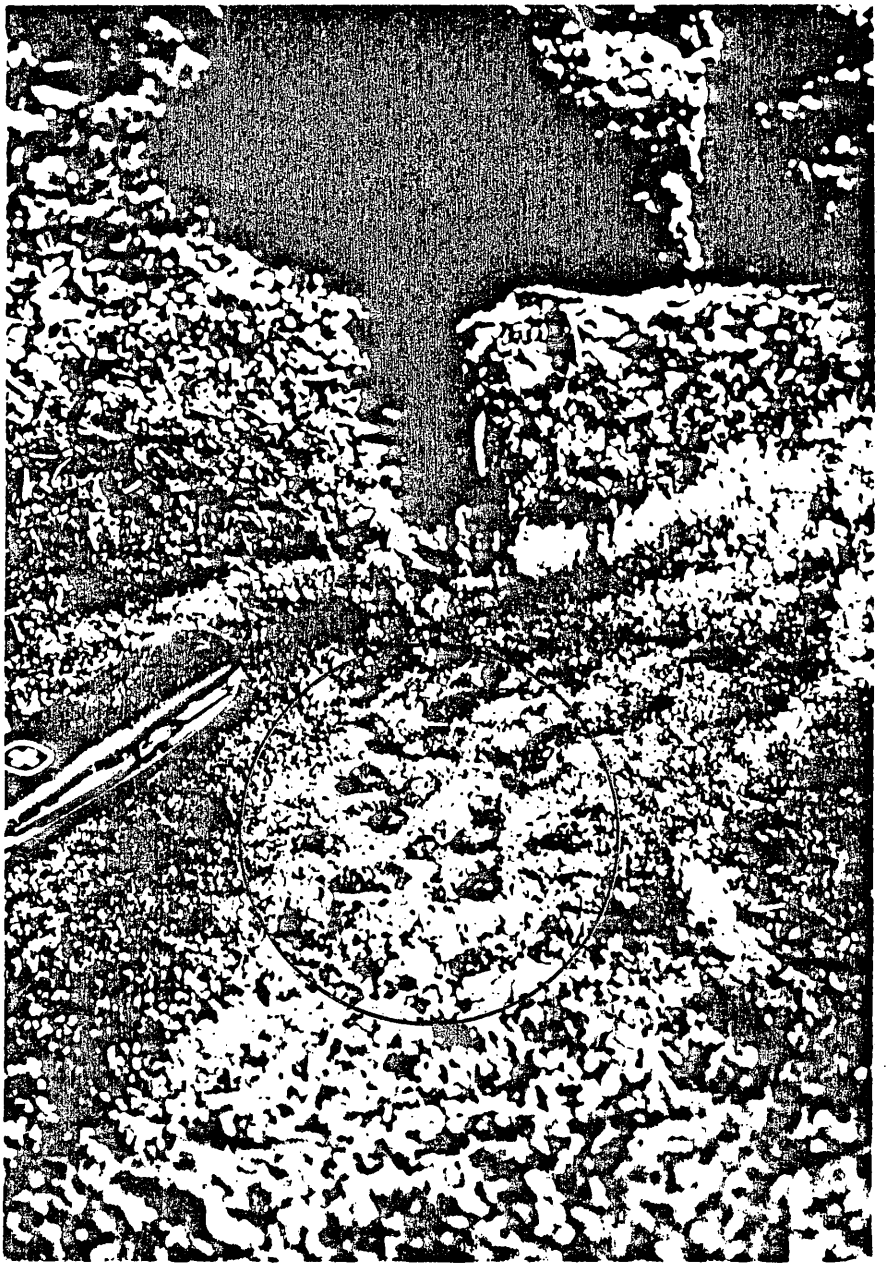

Figure 6. Severe water-repellancy, indicated by beaded water droplets (circled), 2 to 3 centimeters below the surface at Ouzel West. The soil here was incised by a shallow rill.

area here, only one exhibited weak water-repellency; 8 soils showed no indication of non-wettability whatsoever. Other studies have reported this reduction in hydrophobic effects over time after burning (DeBano and Rice, 1975). This is probably related to relatively rapid decomposition of hydrophobic compounds in the surface soil in exposed sites.

Other Soil Properties

Soil organic matter content showed wide variability, both within burns (all burn-intensity conditions) and in unburned soils. Relatively large quantities of organic material were evident in many of the soils taken from the most recently burned areas. This is because considerable amounts of charcoal and ash remain on the surface after burning and much of this gradually becomes mixed into the upper few centimeters of the mineral soil. Along with the dispersion of mineral fines by raindrop splash, this addition of ash to the soil may assist in sealing the surface, thereby reducing infiltration.

Comparison of soil organic content in the severely-burned soils of newer burns (Bear and Pierson) with that in the older burns (Ouzel, Winiger and Comforter) by means of a t-test showed that differences were significant at the 0.05 level (higher organic content in the newly burned soils). Reduced organic content in older burned soils is probably a reflection of the continued removal of loose charcoal and ash by water and wind as well as increased oxidation of organic residues in exposed sites. Though sediment traps generally collected considerably more organic material than was found in adjacent soils at all study areas,

results discussed earlier showed that organic yield declines over time as a result of these effects.

Bulk density was extensively sampled in the field at Pierson and Comforter. Surface soil bulk density in severely-burned areas at both locations was greater than that in the unburned forest nearby. Differences were significant at the 0.05 level at Pierson; the difference at Comforter was only significant at the 0.10 level. Between-burn comparison indicated that the average bulk density of the burned soils at Comforter was generally higher than that at Pierson. However, a t-test specified a significant difference at only the 0.10 level of confidence.

Increased bulk density in burned as opposed to unburned soils is probably due to a number of factors. In part it may be from the removal of coarse organic residues (duff) normally found mixed into the upper few centimeters of mineral soil in the unburned forest. It also probably reflects both the translocation of fines down into the profile as a result of raindrop impact and net removal of the finer size fractions in wash. The higher bulk density at Comforter reflects the development of a lag gravel at the surface as a result of these processes.

Overall, severely-burned soils exhibited a lower level of aggregation (as measured here) than moderately-burned, lightly-burned and unburned soils, which were similar. A t-test showed that the difference was significant at the 0.05 level. The lowest level of aggregation occurred in severely-burned soils at the oldest sites. Reduced aggregation in these soils is partly a reflection of the processes which contribute to increased surface soil bulk density in these situations. Especially low levels of

aggregation in the older severely-burned soils probably results from the mechanical breakdown of these rather weak structures by raindrop impact and frost action in exposed sites as well as the decay of fine root networks.

In finer-textured soils, both increased bulk density and reduced surface soil aggregation should contribute to decreased macropore volume and reduced surface infiltration rates. However, it is not clear that these effects are especially important in coarse-textured soils where particle-size dictates high hydraulic conductivity. Comforter and Ouzel East, which experienced the least soil loss, have the lowest levels of aggregation as measured here.

Multiple Regression Analyses

Stepwise multiple regression analysis was performed on all measured site variables using sediment yield as the dependent variable ($\hat{y}$). Sediment yield was taken as the common logarithm of the weight (grams) of total mineral sediment collected in traps over the course of the period of record at the study areas. The sediment yield data was transformed to correct for pronounced skewness in its distribution. Among the independent variables, aggregation and surface roughness were similarly transformed.

Regression on all variables showed that while many were correlated with erosion they were also highly intercorrelated so that the effects of collinearity are great. To reduce these effects, a principal-components factor analysis was performed on the combined matrix of all measured independent variables from all study areas. Three principal components were derived by this

method and the variable with the highest loading on each component (after varimax rotation) was identified as a "best variable" and used in the analysis of the data for each study area (Bear, Pierson, Ouzel and Comforter).

These independent variables are:

x_1 - Percent bare ground: the area of mineral soil upslope of sediment traps not covered by litter or vegetation, as estimated with the quadrat.

x_2 - Compressive strength: the average bearing strength of the surface as determined from 10 measurements with a portable penetrometer in the area immediately upslope of sediment traps.

x_3 - Aggregation: the percent proportion of smaller primary particles (sand-silt-clay) combined into structures greater than two millimeters in diameter; this value was log-transformed to correct for skewness in the distribution.

The results of the regression analyses for each study area were interpreted only through the steps where beta value significance remained greater than the 0.10 level. Resulting regression equations for each of the study areas are given below:

Bear: $\hat{y} = 8.64 - 1.27x_2 - 3.86x_3$, $R^2 = 0.62$ (Signif. = 0.013)

Pierson: $\hat{y} = -0.369 + 0.031x_1$, $R^2 = 0.79$ (Signif. = 0.000)

Ouzel: $\hat{y} = -3.03 + 0.044x_1 + 1.74x_3$, $R^2 = 0.81$ (Signif. = 0.000)

Comforter: $\hat{y} = -2.04 + 0.032x_1 + 2.33x_3$, $R^2 = 0.62$ (Signif. = 0.033)

The most striking result apparent in these equations is that while percent bare ground (the cover variable) explains the largest share of the variance in soil loss at Pierson, Ouzel and Comforter, this variable does not enter into the equation for Bear.

The absence of cover as a factor in soil loss at Bear may be due, at least in part, to the severe water-repellancy exhibited by the soils at this site. While laboratory tests indicated that the soils at Pierson were also strongly water-repellent, field observations suggest that water-repellency was much more ubiquitous and uniform at Bear. Extensive and widespread surface wash was observed at Bear, even in moderately-burned areas where fresh needlefall covered much of the surface. This effect was not observed at Pierson Park.

Aggregation exhibits a reversal in its influence on soil loss at Bear compared to its effect at Ouzel and Comforter, suggesting that the effect of this variable is complex. At Bear, where aggregation accounted for 50 percent of the variance in soil loss, the relationship between aggregation and sediment yield is inverse. This is consistent with general findings elsewhere that aggregation increases particle resistance to detachment (Bryan, 1974; Evans, 1980). In contrast, at Ouzel and Comforter, degree of aggregation is of secondary importance in explaining soil loss and shows a direct relationship with sediment yield.

The reversal in the way this variable influences soil loss may be the result of a threshold condition dependent upon the

magnitude of aggregation in the surface soil. The proportion of the soil combined into aggregated structures was greater at Bear than at Comforter or Ouzel. While aggregation in the sampled soils at Bear averaged 21.5 percent, it averaged only 5.6 percent at Ouzel and 4.1 percent at Comforter. This suggests that where a relatively large proportion of the soil is combined into these structures they impart some resistance to erosion. On the other hand, where only a small proportion of the surface soil exhibits this aggregated condition erosional losses are enhanced: these aggregates are not bound up into the generally loose surface soil matrix and thus are readily detached.

Many variables that were expected to be of importance in explaining soil loss were not included in these analyses. Slope gradient, for example, is an important factor in erosion (with all other factors held equal) because of its direct influence on the competence of overland flow. However, slope is also highly interactive with other site properties (Meyer et al., 1975; Thornes, 1980). For example, Meeuwig (1971b), in plot studies conducted on a variety of mountain soils, found that the effect of slope on soil loss was highly dependent on the extent of groundcover, which was determined to be the most important single factor explaining erosion.

DISCUSSION

Burn Intensity and Erosion

Burn intensity is an exceedingly important factor in erosion potential. The degree of soil loss in areas experiencing different levels of burn severity appears to be primarily related to

the extent to which the forest floor is removed. Low levels of post-fire erosion in areas subjected to less than severe burning, mainly because of the maintenance of at least some groundcover, has been reported in many studies (Rowe, 1955; Cooper, 1961, Campbell et al., 1977). In unburned areas, the forest floor inhibits erosion by shielding the soil surface from raindrop impact, thereby maintaining high infiltration rates. In addition, the high water-holding capacity of litter, duff and humus reduces the absolute amount of water delivered to the soil. By providing depression storage, litter also detains water on the surface if infiltration-excess precipitation occurs, preventing unchecked overland flow (Clary and Ffolliott, 1969; Plamondon et al., 1972). These functions are at least partly maintained in lightly- and moderately-burned locations.

Groundcover density averaged only 13 percent in severely-burned areas at Bear and Pierson. Measured soil loss in all study areas occurred mainly in severely-burned sites: of 38 sediment traps in these locations, all accumulated measurable quantities of mineral sediment. In contrast, 16 out of 22 traps in moderately-burned, lightly-burned and unburned locations collected no sediment.

In lightly-burned areas, minor amounts of material did collect in some traps where rainsplash could occur on bare areas within the lightly scorched but otherwise intact litter cover. Similar quantities of splashed soil were collected in traps situated within breaks in the litter cover in unburned forest. Groundcover density in lightly-burned areas at Bear and Pierson averaged 78 percent; though not directly measured, groundcover density in

unburned areas nearby appeared similar. Other than this minor soil movement due to splash, no evidence of appreciable soil loss was observed in areas of low-intensity burning at any of the study sites.

In moderately-burned sites erosional losses also tended to be slight. Though much of the groundcover may be removed by fire in these areas, post-fire needlefall from scorched tree crowns generally restores at least some groundcover relatively quickly, thereby limiting erosion. This effect has been reported in other studies (Connaughton, 1935; Hendricks and Johnson, 1944; Megahan and Molitor, 1975; Campbell et al., 1977).

Groundcover density averaged 61 percent in moderately-burned locations at Bear and Pierson and much of this consisted of a thin layer of fresh needlefall. A groundcover density of 60 to 70 percent appears to be a general threshold value for preventing serious erosion in many areas (Copeland, 1965; Meeuwig and Packer, 1976).

Serious soil loss did occur in a moderately-burned site at Bear: two traps here collected 739.5 and 1004.7 grams of mineral sediment. However, two other traps in the same area collected no sediment. When visited three weeks after the burn, this slope was already coursed by numerous braided wash features even though little rain had fallen by this time (Figure 7). Thus, surficial erosion in this location appears to be the result of prevasive water-repellency in the soil. However, observations at the other study areas suggest that erosion here will probably soon decline to negligible levels as needlefall continues to restore groundcover and as water-repellency diminishes over time.

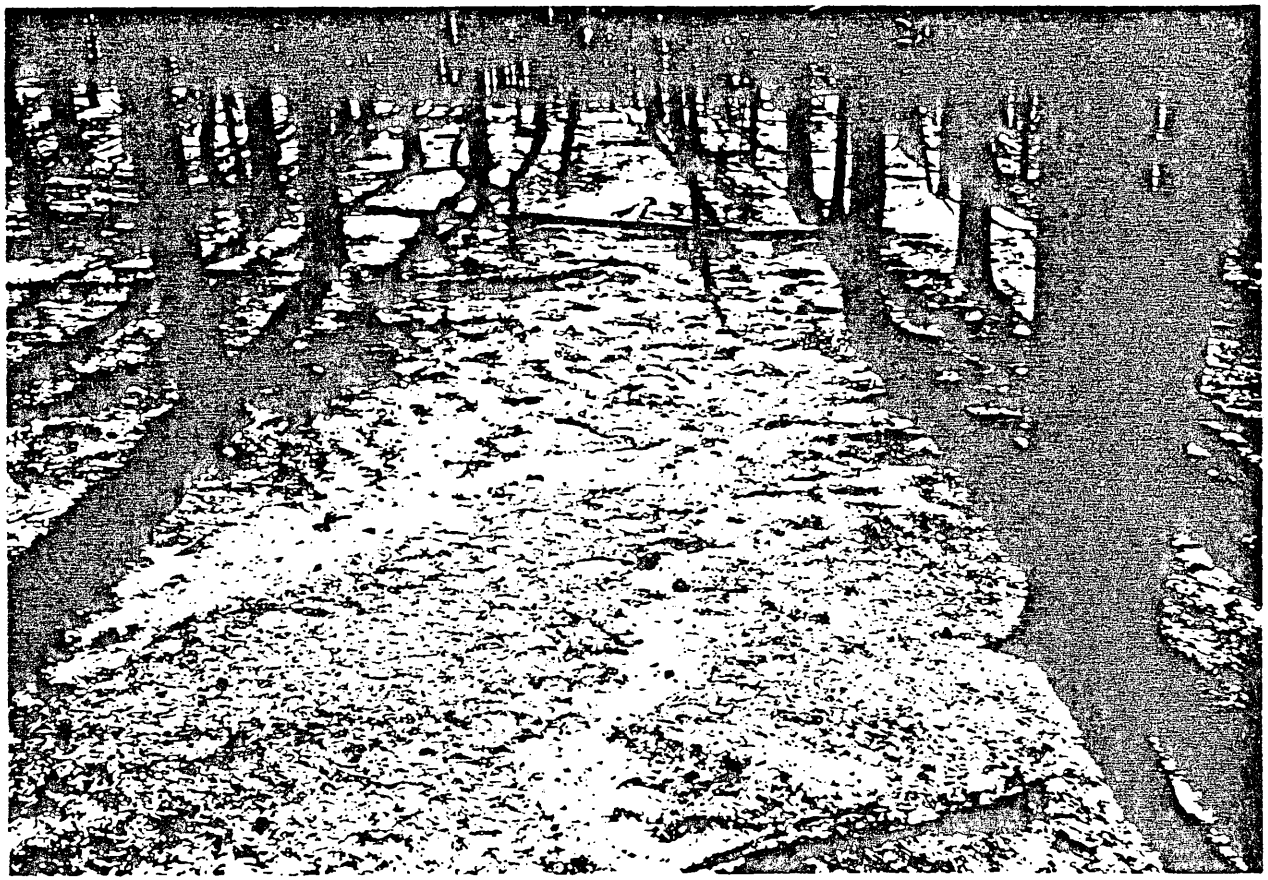

Figure 7. Widespread surface wash in a moderately-burned site at Bear. Photo was taken 3 weeks after the fire.

Influence of Site Characteristics on Sediment Yield

Where most of the vegetative and litter cover has been removed, as in severely-burned locations, erosion is inevitable. However, sediment trap and surface elevation change data, as well as observations in the field, indicated that erosion was areally non-uniform in all study areas. Discontinuous, unconfined slopewash appeared to be the dominant erosional process in actively eroding areas, at least during this particular period of study. Even in areas experiencing the most soil loss, rilling was not very evident.

Erosion at a particular location cannot be directly equated with sediment yield from the site. Much of the material mobilized on hillslopes in this terrain moves only a short distance downslope and does not reach permanent channels, an effect which has been reported by other investigators (Cooper, 1961; Striffler and Mogren, 1971). Because of high microtopographic roughness there is abundant opportunity for sedimentation on the hillslope.

Deposition apparently occurs primarily where overland flow is ponded by larger surface roughness features such as downed logs, the buttresses of standing trees, exposed boulders and bedrock outcrops. These sediment storage sites clearly have an important mitigating influence on limiting erosional loss from the hillslope proper (Figure 8). In some cases, on-slope sedimentation also appears to result from changes in surface infiltration capacity due to subsurface discontinuities such as shallow depth to impermeable bedrock or the occurrence of water-repellent layers. In other cases deposition occurs on flatter slope segments.

Figure 8. Sediment deposition on the toeslope at Ouzel West. Sedimentation here results from both reduced slope gradient and the damming of overland flow by larger debris on the surface.

Though severe burning results in accelerated erosion, net loss from hillslope to channel is far less than the total amount of soil mobilized after disturbance. Observations at Comforter and Ouzel East indicate that much of this deposited material is stabilized as site recovery proceeds.

Wherever the edge of a severely-burned area does not coincide with a watercourse or road it will be bordered by a buffer zone consisting of moderately-burned and lightly-burned areas which, in turn, merge with unburned forest. In these cases, any mobilized soil not deposited in the burn will be trapped in the rough forest floor within this perimeter. This further reduces the potential for sediment yield to the drainage network.

Source Areas for Sediment Yield to the Drainage Network

In addition to wide variations in soil loss both along and across individual hillslope profiles, the magnitude of erosion at all sites varied areally with topographic position. The greatest amount of erosion at all study areas observed during the field season occurred within channel extensions on the hillslope (contour concavities or hollows). Sediment traps within these topographic situations collected far more material than traps located on essentially straight-contour hillsides. At Ouzel West, two traps in a steep hollow collected 2267.2 and 3439.9 grams of mineral sediment over the study period, several times the average amount collected in traps along the straight-contour slope. Similarly, at Comforter, maximum soil movement was recorded in a shallow post-burn gully in the bottom of a broad hollow: 999.3 grams of mineral sediment accumulated in the trap in this

gully (compare with 186.0 grams maximum accumulation in the open hillslope traps at Comforter). Early post-burn erosion had apparently been concentrated in this location, as indicated by extensive deposits of now-stabilized sediment in the unburned forest below.

Two first order channel extensions in severely-burned locations at Bear and Pierson experienced high flow events during the study period. This resulted in the deposition of large quantities of eroded material, including much cobble-sized debris, behind wire dams erected in the channels. A painted cobble ($D_{\bar{x}}$ = 8.5 cm) from a profile station within the channel at Bear, which was found in the dam deposit there, had been carried 12 meters by the flow. At both areas, debris indicated that high flow had exceeded 20 centimeters in depth and channel sideslopes showed signs of having been scoured by a continuous sheet of overland flow. Similar channelways in unburned areas near these study sites showed no evidence of overland flow at any time during the field season.

Though actual soil loss from burned area to streams was not directly observed during the study period, the preceding observations indicate that sediment yield from hillslope to active drainage network must occur primarily from established channel extensions. Toeslope sites adjacent to stream channels should also be primary locations for sediment yield. During storms, converging flow lines apparently lead to widespread overland flow in these areas, providing the best opportunity to move sediment over long distances. These conclusions are consistent with the partial-area concept of storm runoff generation, indicating that

saturation overland flow should be preferentially produced in near-channel areas (Engman, 1974; Chorley, 1978).

In contrast, middle and upper hillslope situations, distant from channel extensions, are unlikely to contribute significant quantities of sediment to streams. Though rainsplash and overland flow will mobilize large quantities of material in these areas, the abundance of depositional sites on the slope surface clearly limits soil loss. In addition, discontinuous overland flow appears to be the dominant sediment transport process in these locations, at least under the rainfall conditions occurring during this period of investigation. Short distance transport by this means is incapable of moving large amounts of soil to distant streams, at least over shorter time periods.

Reduced Erosion Over Time

Rapid decline in erosion over time after fire, in most cases within only a few years, has been reported in a large number of studies (Orr, 1970; DeByle and Packer, 1972; Campbell et al., 1977). This has usually been attributed to vegetative recovery. In this study, observations at five burns of different age suggest a similar decline in soil loss over a relatively short period of time (2 to 4 years). Two principal factors are responsible for this.

Both observations in the field and textural analysis suggest that surface armouring is important in limiting erosion over time in disturbed soils in the Front Range. As accelerated erosion after burning depletes readily erodible material from the soil surface, a lag gravel concentrate develops which tends to

check further erosion. Megahan (1974) attributed the rapid decline in erosion in severely-disturbed granitic soils in Idaho to the development of an erosion pavement of this kind. He noted that erosion diminished before any significant vegetation growth occurred.

Soil water-repellancy, while occurring naturally under coniferous forest in this area, does appear to be intensified by burning. Data also suggest, however, that water-repellency in severely-burned soil declines to lower levels than that occurring in unburned forest after a few years. This should improve the infiltration characteristics of the soil in older burned areas, thereby reducing the potential for overland flow.

Vegetative recovery appears to have little effect in declining erosional losses over the short time spans with which this study has been concerned. Ouzel East experienced relatively slight erosion despite a virtual absence of vegetative regrowth at this site. Though considerable herbaceous growth was evident at Comforter four years after the burn there, much bare ground remains between plant stems and groundcover density averaged only 47 percent at stations in the high-intensity burn area. Splash erosion is still active since very little litter cover has returned to this area. Litter cover provides more protection to the soil surface than herbaceous growth (Packer, 1951; Dyrness, 1967). Over longer time spans, regrowth of forest vegetation and renewal of the forest floor will undoubtedly provide the best protection against erosion in severely-burned areas.

CONCLUSIONS AND RECOMMENDATIONS

Erosion potential after wildfire is limited primarily to areas experiencing severe burning. Even in these locations, however, subaerial erosion is not uniform over the surface because of the high capacity of the hillslopes to store eroded debris. Because of this, sediment yield to streams occurs mainly from near-channel sources where periodic flushing by storm and/or snowmelt events moves accumulated material towards the active drainage system. This suggests that fire control and post-fire rehabilitation efforts should be concentrated in these areas in order to reduce erosional impact on the stream environment. Maintenance of a buffer zone of lightly-burned or unburned vegetation and forest floor in these areas would greatly restrict soil loss to the drainage network.

Lightly- to moderately-burned sites are subject to much less soil loss because groundcover is maintained or at least rapidly restored by post-burn needlefall. Consequently, prescribed burning, resulting in low levels of burn intensity, should have little erosional impact in this area. Newly burned areas which have been subjected to moderate burning may experience some soil loss because of water-repellancy in the surface soil and delay in the resupply of groundcover by needlefall. However, observations at Bear indicated that even sparse litter cover retards runoff, thereby limiting widespread soil loss.

In severely-burned locations, erosional losses rapidly decline over time as erosion pavement develops and as surface water-repellancy is reduced. Nevertheless, threshold conditions for erosion will remain well above that of the unburned forest for many years.

Losses of both organic material and mineral fines in severely-burned areas seem to have an important effect on site productivity. For example, no conifer reproduction was observed at Comforter and the recovery of aspen and woody groundcover species was limited to small areas. Excessive exposure in severely-burned areas also appears to be an important factor in reduced site productivity. Full restoration of surface resistance to pre-burn levels must await recovery of the forest floor and overstory. The occurrence of a severe storm during this period, which cannot be predicted, could re-mobilize deposited sediment within the burn. In such an event, the greatest danger of stream contamination by sediment is from the flushing of material stored in channel extensions. These deposits were observed just below the burn perimeter at several of the study areas. The installation of check dams in these locations would mitigate this hazard.

Though not directly evaluated in this study, roads are clearly one of the principal sources of soil loss in burned areas. As fuelbreaks are constructed in the fire control effort, the size of the road network is substantially increased. Any effort to reduce erosional losses from burned areas should include the application of remedial stabilization measures and periodic maintenance to roads.

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